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A FEASIBILITY STUDY OF LIFE-EXTENDING CONTROLS FOR AIRCRAFT TURBINE ENGINES USING A GENERIC AIR FORCE MODEL (PREPRINT)

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Turbine engine controllers are typically designed and operated to meet required or desired performance criterion within stability margins, while maximizing fuel efficiency. The U.S. Air Force turbine engine research program is seeking to incorporate sustainable cost reduction into this approach, by considering a life-cycle design objective if the life of the engine is considered as an objective during the design of the engine controller. Specifically during aircraft takeoff, the turbine engines are subject to high temperature variations that aggravate the stress of the material used in their construction and thus a negative effect in their life spans. Therefore, the control strategy needs to be re-evaluated to include operating cost, and extending the life of the engine is one way to reduce that. Life-Extending Control (LEC) is an area that deals with control action, engine component life usage, and designing an intelligent control algorithm embedded in the FADEC. This paper evaluates the LEC, based on critical components research, to demonstrate how an intelligent engine control algorithm can drastically reduce the engine life usage, with minimum sacrifice in performance. Finally, a generic turbine engine is extensively simulated using a sophisticated non-linear model of the turbine engine. The paper concludes that LEC is worth consideration and further research should include development of the damage models for turbine engines, and experimental research that could correlate the damage models to actual damage for turbine engines. This could lead to implementation of online damage models in real-time that will allow for more robust damage prevention.

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ABSTRACT

Turbine engine controllers are typically designed and operated to meet required or desired performance criterion within stability margins, while maximizing fuel efficiency. The U.S. Air Force turbine engine research program is seeking to incorporate sustainable cost reduction into this approach, by considering a life-cycle design objective if the life of the engine is considered as an objective during the design of the engine controller. Specifically during aircraft takeoff, the turbine engines are subject to high temperature variations that aggravate the stress of the material used in their construction and thus a negative effect in their life spans. Therefore, the control strategy needs to be re-evaluated to include operating cost, and extending the life of the engine is one way to reduce that. Life-Extending Control (LEC) is an area that deals with control action, engine component life usage, and designing an intelligent control algorithm embedded in the FADEC. This paper evaluates the LEC, based on critical components research, to demonstrate how an intelligent engine control algorithm can drastically reduce the engine life usage, with minimum sacrifice in performance. Finally, a generic turbine engine is extensively simulated using a sophisticated non-linear model of the turbine engine. The paper concludes that LEC is worth consideration and further research should include development of the damage models for turbine engines, and experimental research that could correlate the damage models to actual damage for turbine engines. This could lead to implementation of online damage models in real-time that will allow for more robust damage prevention.

INTRODUCTION

Modern control system designers must consider an ever-increasing number of constraints and objectives. In general, as soon as a designer has developed a control solution that meets stability and some minimum performance requirements, it becomes necessary to improve on the original design. Perhaps a simpler design is all that is desired. Possibly the minimum performance requirements were simply not good enough due to some unforeseen operational requirement. Maybe, other objectives were not considered in the original design; therefore, the next logical step is to consider these new objectives.

Numerous approaches for incorporating these other objectives have been proposed. If controller stability and simple requirements, such as rise time and overshoot for a simple linear system, are all that need be considered, then a modern control tool such as root-locus design [10] may be all that is required. For non-linear or Multiple-Input Multiple-Output (MIMO) systems, the list of approaches becomes more extensive. Furthermore, gain scheduling and adaptive control are required on systems with non-linearities due to changing environment or other uncertainties in the system.

Until now, this discussion has hardly scratched the surface of potential scenarios requiring more complex controller design approaches.

The U.S. Air Force turbine engine research program seeks to incorporate yet one more objective into the turbine engine controller design. Sustainment costs (maintenance, upkeep) could potentially be reduced if the life of the engine could be considered as an objective during the design of the engine controller. Sustainment here is that activity of the life cycle management of a constructed turbine engine that is necessary to keep it in good condition. If sustainment is not maintained at adequate levels, the turbine engine will degrade, and over time continue to degrade. Research accomplished under the titles of 'Life-Extending Control (LEC)' and 'Damage-Mitigating Control' has shown that reducing sustainment efforts may be possible.

Perhaps the most important aspect of LEC is the identification of the type of damage that is to be mitigated.

Mattingly et al. [1] discuss the following considerations in terms of the life of the engine components: airfoil bending, flutter; unsteady aerodynamic forces such as buffeting and high cycle fatigue (HCF), thermal differential stress (or thermo-mechanical fatigue, TMF) and low-cycle fatigue (LCF), local stress concentrations, foreign object damage (FOD), bird strikes; inertial and gyroscopic forces during strenuous maneuvers, and material composition or chemistry effects, such as erosion, corrosion and creep. Jaw et al. [2] found that, 'TMF, creep and rupture are the prime candidates for damage control and life extension on a continuous-operation basis.'

Many different approaches have been researched for LEC of aircraft turbine engines. The similarity between them is the damage model, which is used as the criterion for determining the degree to which the life is extended. Caplin's [3] damage model was a computation of the normalized crack damage in continuous time. This computation was then used to change the controller input and/or the set-point.

Tangirala [4] is perhaps the only published work that implements LEC on a physical experiment. A shaker table was used to induce the fatigue damage on a two degree-of-freedom (DOF) system, which was predicted to fail at a hole located in one of the system's connecting links. The results showed that the life extension successfully reduced the damage and increased the life by a factor of ~3.5 times over the baseline.

Tangirala [5] derives a state space model for crack growth rates on the fan and compressor guide vanes, thereby allowing for a continuous time damage model that can estimate the damage accumulation and the damage rate. Life-extension control similar to that of Caplin [3] was then employed, with the exception that the fan and compressor guide vane optimal schedules became further inputs to the turbine engine. One other distinction from Caplin [3] is that the damage mitigation was implemented as an 'offline', instead of an 'online' process.

Jaw [2] and Guo [6] both reported on mitigation of the thermo-mechanical fatigue (TMF) of a turbine engine during aircraft takeoff. Both modified the acceleration schedules slightly, which resulted in less TMF damage, at higher rise times for low speed spool, high speed spool and consequently thrust. Reduction of damage was relatively high and the increase in rise time was very small, so the benefits clearly outweighed the disadvantages.

The Turbine Engine Dynamic Simulator (TEDS) at the Air Force Research Lab's Propulsion Directorate on Wright-Patterson Air Force Base, is a suitable, generic, test bed for verification of LEC. The ICF consists of two simulators which have hardware interfaces for actual aircraft engine inputs and outputs. Real-time processors run the simulation code for each simulator. One is typically configured to operate as a Full-Authority Digital Electronic Controller (FADEC), while the other processor operates as a simulated generic turbine engine.

Operation of a military fighter aircraft engine has some special considerations. LEC is premised upon the fact that the performance of the engine and the life of the engine will be in opposition of each other. In order to increase life, the performance will have to be compromised; the converse of this is also true. A military fighter aircraft will have some additional objectives during certain aspects of the mission profile, which will preclude consideration of the life of the engine alone. During a dogfight, the turbine engine controller will hardly be able to consider the cannon fire or the heat-seeking missile that must be evaded. Maximizing performance during this period of the flight will be crucial to the life of not just the engine, but the entire aircraft. Further, the successful accomplishment of a particular aircraft's mission may be crucial to the life of other aircraft, personnel, or for successful accomplishment of other military objectives. However, one assumption, which will hold nearly universally in reality, is that during the aircraft takeoff, the performance may be optimized with the life of the aircraft, with little or no detriment to the success of the mission.

SIMULATION SETUP

The generic engine model is a detailed, physics-based engine model of a two-spool, non-augmented, low bypass ratio engine developed using MATLAB/Simulink® [9]. The model captures mechanical dynamics and thermodynamics associated with a low thrust commercial / military jet engine used for regional, corporate and military applications. The generic engine model is a nonlinear state variable model represented by state equations,

$$\dot{x} = f(x,u,t), \tag{1}$$

Where the state vector, *x*, consists of temperatures, pressures, flow rates, and mechanical speeds in the engine and the input vector, *u*, consists of fuel flow valve actuation, power lever angle and atmospheric conditions. A subset of measured engine states given by

$$y = g(x) \tag{2}$$

is available to the controller for determining control actions. The controller used in this simulation effort is an extension the controller described in [9] based on the NASA's Modular Aerospace Propulsion System Simulation (MAPSS). The simulated controller has been extended to implement and validate LEC concepts suggested by Guo, et.al in [6] to optimize engine spool acceleration schedules in order to mitigate damage due to TMF. A block diagram of the simulation setup is shown in Figure 1. This paper optimized the acceleration schedule

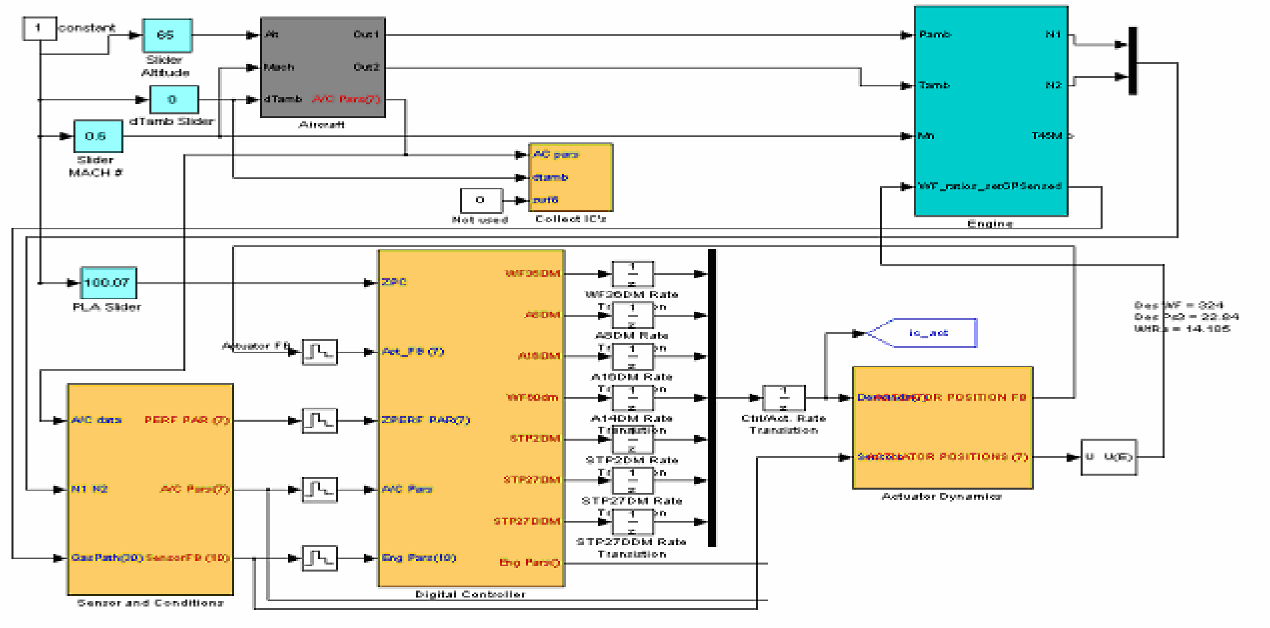

Figure 1: Schematic Diagram of Engine and Controller for Generic Simulator

such that the damage to the engine from TMF was minimized, yet the rise time requirement was met. For this simulation several assumptions had to be made.

1) In lieu of having a rise time requirement, the generalized model before modification will be utilized as a baseline for comparison of the LEC modified model. Whether or not the LEC rise time meets the real-world requirements is indeterminate; however, comparing the LEC rise time to the baseline will demonstrate any performance tradeoffs.

2) In lieu of having a damage model, the turbine engine temperatures are compared between the baseline and the LEC model. Any reduction of peak temperature in the LEC model is assumed to be damage mitigating, and any increase in temperature is assumed to be damage enabling.

3) Optimization of the acceleration schedules was performed using an ad hoc iterative approach. The optimization accomplished by Guo [6] requires not only a rise time input, but also a damage model. The acceleration schedule selected for the Air Force model meets the form and function of Guo's [6] and is shown in Figure 2.

The flight profile under consideration is a takeoff profile, where the Power Lever Angle (PLA) undergoes a step input. Acceleration of the engine spools and the engine temperatures are expected to be similar to that shown in Guo's [6] paper. Specifically the rise time would increase and the temperatures would decrease.

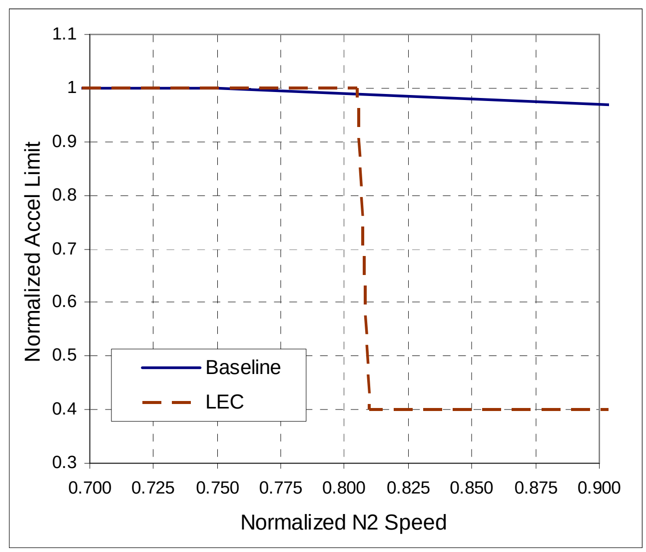

Figure 2: Comparison of Baseline and LEC Acceleration Schedules.

RESULTS

Simulation of the LEC and the baseline model are shown in the following figures. Figures 3 and 4 compare the baseline and LEC for low speed spool, N1. Figure 3 shows a magnified portion of the plot for the region where the two curves are different.

Figures 5 and 6 compare the baseline and LEC for high speed spool, N2. Figure 6 shows a magnified portion of the plot for the region where the two curves are different.

Figures 7 and 8 compare the T3 temperatures of the baseline and the LEC. Figure 8 shows a magnified portion of the plot for the region where the two curves are different.

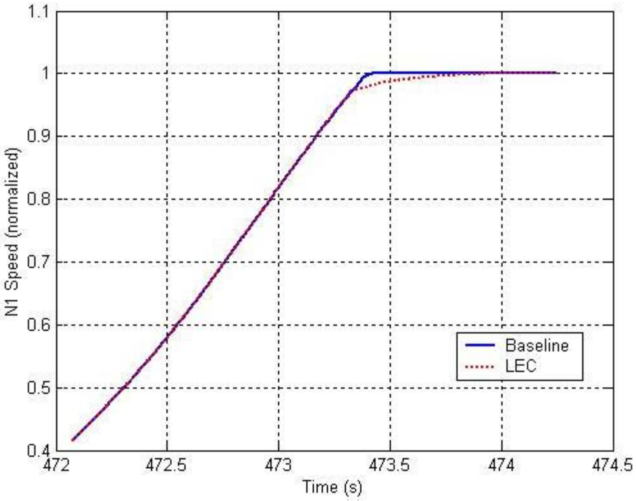

Figure 3: Comparison of low speed spool speed, N1.

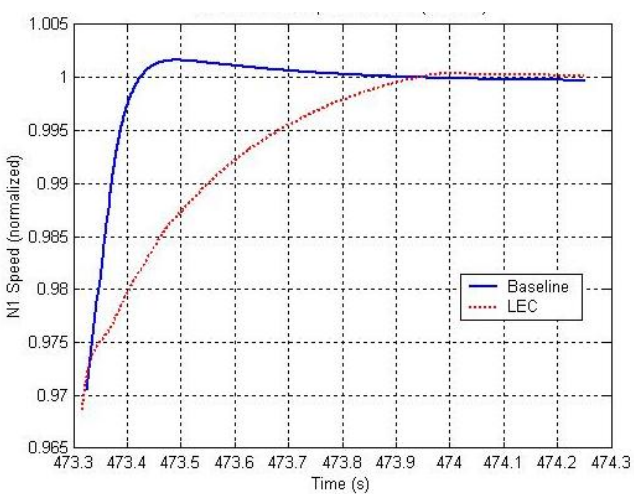

Figure 4: Zoomed comparison of low speed spool speed, N1.

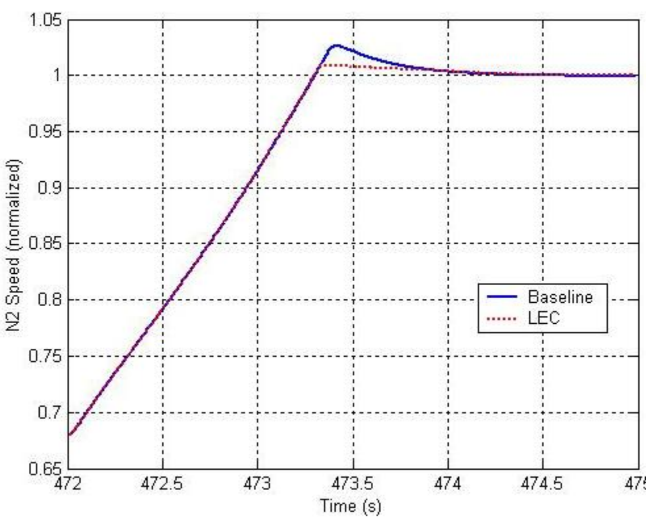

Figure 5: Comparison of high speed spool speed, N2.

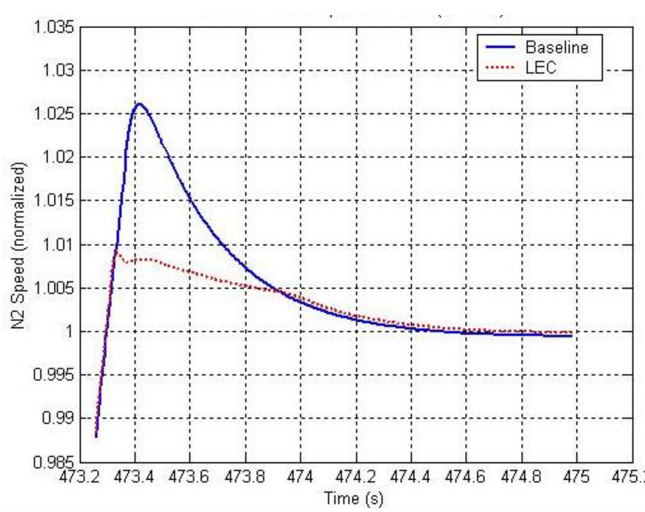

Figure 6: Zoomed comparison of high speed spool speed, N2.

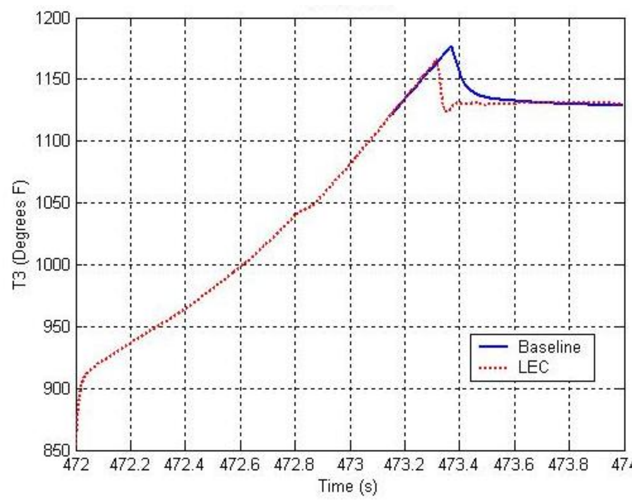

Figure 7: Comparison of engine compressor temperature, T3.

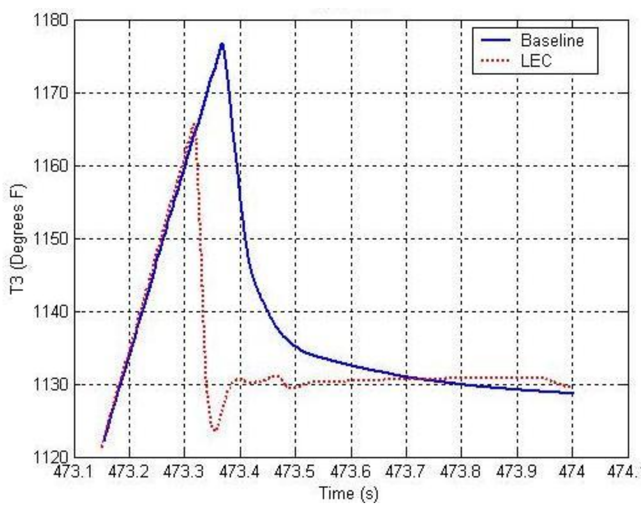

Figure 8: Zoomed comparison of engine compressor temperature, T3.

Figures 9 and 10 compare the T45 temperatures of the baseline and the LEC. Figure 10 shows a magnified portion of the plot for the region where the two curves are different.

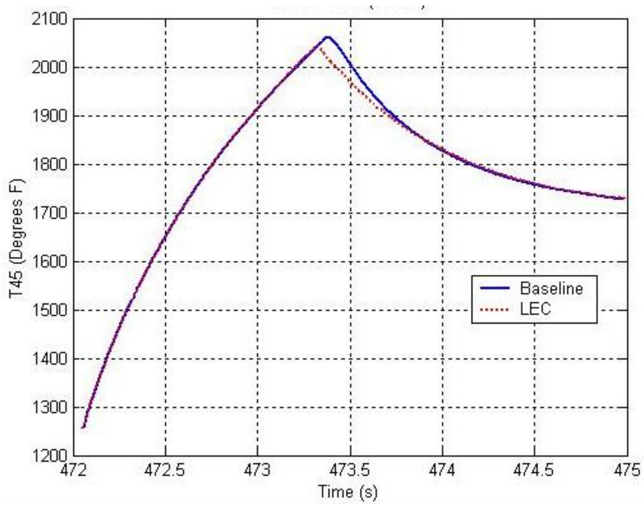

Figure 9: Comparison of turbine temperature, T45.

DISCUSSION

Examining Figures 2-5 shows that the rise time of the turbine spool speeds for the Baseline and LEC are very similar. In fact, based upon the 95% set point criteria, the rise times are identical. This indicates that the desired performance is still met despite the implementation of a more conservative acceleration schedule. As a result of implementing the LEC, the T3, and T45 temperatures were lower by 11 ºF and 16 ºF, respectively, as seen in Figures 6-9. What this shows is that using a more conservative acceleration schedule can result in lower engine temperatures, without having to modify the performance significantly. Theoretically, if the engine temperatures are lowered, the engine damage due to TMF should be reduced.

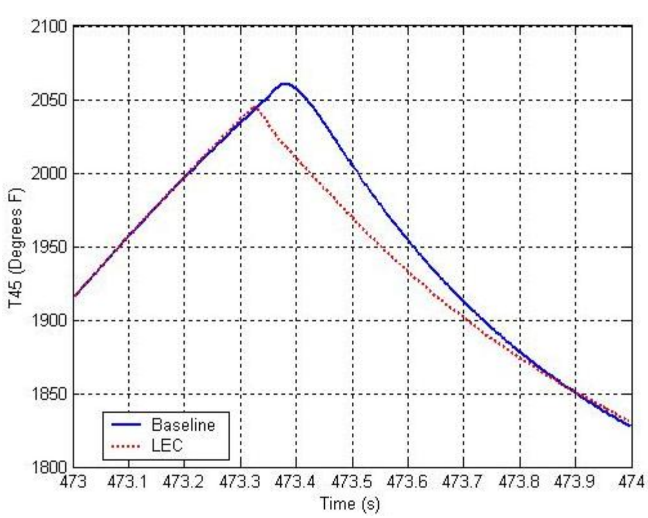

Figure 10: Zoomed comparison of turbine temperature, T45.

CONCLUSIONS

LEC's goal is to expertly manage the operation of the turbine engine, such that the cost of controlling the engine is optimized with respect to its performance. If this is accomplished, the result should be satisfactory engine performance and reduced damage. The simulations performed herein have emulated most of the aspects of that work to compare and contrast the results using a generic Air Force turbine engine model. The generic model simulation showed similar results to Guo [6], and hence the acceleration schedule modification approach is valid.

Further research should include development of the damage models for turbine engines, and experimental research that could correlate the damage models to actual damage. Tagirala [8], provides the most helpful published correlation between the damage model and the experimental trial for a simple 2 DOF system. Development of similar research for turbine engines could lead to implementation of online damage models in real time, which will allow for more robust damage prevention.

Although factors such as creep and creep rupture are primary damage modes for turbo-machinery, these damage modes are further aggravated by extreme temperature cycles. Reducing temperature variations, particularly on the hot side of turbine engines, is an important factor for extending critical component life times.

It is well known that transients of any kind in turbine engine components have an impact on engine component life. In military turbine engines, components are tightly coupled from the front to the back of the engine. A control policy that reduces engine transients will impact remaining life of critical components. In this work we consider the implementation of LEC concepts directly in the engine controller with no need for off-line data analysis.

APPLICATION AND FUTURE DIRECTIONS

The simplest form of LEC is adapting the use of the engine to suit the mission need, e.g., derated takeoff when the aircraft is light and the field is long. Advanced controls automate these approaches to reduce pilot workload and ensure consistency.

LEC, as in the work reported here, can be a refinement of the conventional control logic, taking into consideration the impact on component life usage in ways that trade minor and imperceptible performance degradation, for significant component life extension. Essentially, we are mitigating highly damaging transient speed and temperature excursions, with modest short term control adjustments.

The control logic for implementation of this approach will in practice need evaluation across the entire operating envelope, to ensure it is benign and meets requirements under any operating condition and control input.

It is possible that this will result in added control modes, e.g., in this demonstration, a mode restricted to operation on the ground and approaching takeoff power. Further opportunities for intelligent design of this nature may come from adaptive control, essentially tuning the adjustment to the baseline control mode to account for engine-to-engine variation. Control algorithms and schedules are available to cope with the worst acceptable new engine, fully degraded and at the end of its useful service life. The limiting factors in new engine performance are many, as are the modes of degradation (e.g., compressor erosion vs. turbine clearance increase), and the control schedules must accommodate combinations of these.

Aircraft engines are often trimmed to a consistent performance level prior to delivery. This extends "good" engine life by derating to match the nominal engine performance, while increasing safety through more consistent aircraft performance. However, this useful technique does not address the issue of in-service degradation. Initial pass off power levels, must allow for loss of power over the increasing intervals between engine overhaul we now expect.

There seems to be significant potential to further trim new engine performance back toward minimum desirable levels, while monitoring engine degradation and periodically trimming the steady state and transient schedules to compensate. This "manual" adaptive control should result in yet more component life extension and extended time on wing; however, this would be unacceptable unless implementation was rigorous and consistent. There is a strong case for automating this process and embedding it in the engine controller, but this requires a robust and dependable means of automatically monitoring, quantifying and classifying degradation, so that appropriate "de-trimming" is made.

The next step could be to exploit existing (e.g., variable geometry) or added (e.g., modulated tip clearance control) control effectors, to provide the most appropriate mitigation for the specific degradation mode and cause. However, these adaptive control approaches primarily address steady state performance.

Moreover, modification of the transient behavior of the turbine engine, the technique described in this paper, may be more powerful, particularly for military engines where component lives are dominated by the effects of transients. A similar roadmap leading to adaptive control of engine dynamic performance and component exposure to damaging speed and temperature transients can be defined.

Transient LEC depends on a detailed in depth understanding and quantification of the impact of usage on component life. Current component lifing models fall short in enabling maximum LEC leverage. More research and analysis of actual service exposure and its impact on component lives is needed to lay a stringer foundation for this evolution.

The next step in this work is to integrate damage and structural models within the engine control logic to revise control policies on-line.

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BIOGRAPHIES

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Alireza (Al) Behbahani, Ph.D. is currently a senior aerospace engineer and senior program manager in the Propulsion Directorate in the Turbine Engine Division (PRTS) at the US Air Force Research Laboratory, WPAFB, where he is the Group lead for Controls and Engine Health Management (EHM). He is involved with JSF related projects, VAATE and SBIR funded projects and others in Controls and EHM underway in industry. He has a BSEE from Utah State, and MS and Ph.D. from the Ohio State University. His research interests include intelligent controls, FADEC, PHM, LEC, MBC, sensors, M&S of gas turbine, controls-related research, development, integration, and testing. Previously he was the project leader / lead engineer-CF6 control systems at the GE Aircraft Engines. In the past, he has also served as an engineering consultant, senior research associate, senior engineer at various positions and a faculty member at the University of Cincinnati, College of Engineering.

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Richard Millar

Richard leads the Science and Technology efforts relayed to Fuel Systems, Control and Diagnostics in Propulsion and Power engineering at NAVAIR. NAVAIR provides engineering, acquisition and technical support to Naval aviation.

He has spent most of the last 35 years in R&D, engineering and management functions in firms using and manufacturing gas turbine engines and their control systems. This experience was at most of the major US aerospace firms: Boeing, Lockheed Martin, BAE Systems, General Electric, Rolls-Royce, Honeywell and UTC.

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